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Review

Driving vehicle dismantling forward - A combined literature and empirical study

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A B S T R A C T

To move towards a more sustainable and circular economy, a more efficient recovery processes for end-of-life vehicles and their constituent components and materials is needed. To enable reuse, remanufacturing, high-value recycling and other circular strategies, a well-functioning disassembly is essential. This article presents a literature review of studies focusing on vehicle dismantling and surrounding end-of-life treatment systems. Furthermore, topics considered as the most critical for practitioners were identified through focus groups composed of industry representatives and researchers from various Swedish organizations. By comparing findings from the literature and empirical results, it is concluded that there are differences and gaps between the areas researched and those considered as important by industry, thus calling for further research to address practical challenges in improving vehicle end-of-life management. The four areas highlighted as the most prominent are: i) plastics, ii) batteries, iii) investments and ownership structures, and iv) the workforce.

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1. Introduction

Vehicles generate economic opportunities and societal advances through transportation of goods and people. Consequently, the number of vehicles in circulation continues to increase globally. However, as other active products (those consuming energy and/or materials in the use phase), vehicles on the roads (and in cities especially) cause negative side effects on the environment during use, but also throughout their life cycle (Böckin et al., 2020; Raugei et al., 2015).

Vehicles are complex products composed of numerous components and diverse materials. End-of-life vehicles (ELVs) are considered as one of the main sources of secondary raw materials. The use of plastics and critical metals are also increasing, mainly due to the embedded electronics and weight reduction efforts (Restrepo et al., 2017). The vehicle fleet holds a great amount of valuable materials, which needs to be recovered, separated, reused and recycled in a safe and efficient way to achieve a circular economy and sustainable society.

Countries and regions are aware of the importance of attaining a high degree of recycling and recovery. The response (in several cases) has been to impose legal requirements on vehicle recovery. As examples 95% of the car weight should be recovered in the EU, according to ELV Directive 2000/53/EU, China required the same rate by 2017 (Ni and Chen, 2014) and Turkey requires 95% recovery rate by 2020 (Demirel et al., 2016). Direct reuse of second-hand and remanufactured components is often a preferred alternative to decrease the environmental impacts from vehicles (Mckenna et al., 2013). To enable efficient and profitable reuse of components and recovery of important low-volume materials as well as high(er) reuse and recycling rates, vehicles needs to be dismantled.

In 2017, dismantling operations were performed by 293 authorized car dismantlers in Sweden (Swedish.Car.Recyclers.Association, 2020). About 190 000 cars reach the dismantlers every year either as natural or premature ELVs (Swedish.Transport.Agency, 2020). The dismantlers depollute the vehicles and disassembles components for reuse as spare parts, material recycling, or sell to remanufacturers. In some cases, mechanical dismantling is used for material recycling, but most of the dismantling is conducted manually by skilled mechanics. After dismantling, the vehicle hulk is compressed and sent to companies where it is shredded and materials sorted. The material fractions are sold to material producers. As a contrast, there are approximately 15–20 dismantlers of trucks. The same procedures are followed as for light vehicles, though, a larger share of the vehicles are exported to get a second life.

Dismantlers and their dismantling operations are important for the sustainability of future ELV systems and therefore need research attention. The authors of this article also acknowledges the importance to approach the area with empirical as well as theoretical studies, and comparing the two to ensure research has practical relevance.

In academia, research efforts have been undertaken in the field of end-of-life treatment, much of it in the last decade (Karagoz et al., 2019). As pointed out by Webster and Watson (2002), research is cumulative and reviewing past results to prepare for the future is important. However, only 22 literature reviews were identified by Karagoz et al. (2019) regarding ELV management between the years 2000 and 2019. Apart from their own review, few concerned the whole ELV chain. Nonetheless, there are reviews comparing different ELV recycling systems e.g. Despeisse et al. (2015); Saidani et al. (2019); Sakai et al. (2014). However, most literature reviews focus on specific issues or parts of the ELV chain, such as Buekens and Zhou (2014); Cossu and Lai (2015); Cucchiella et al. (2016); Dalmijn and De Jong (2007); Siqi et al. (2019). Karagoz et al. (2019), identified 232 articles through the keyword "*End of life*

Table 1
Combinations of keywords through the operator w/1.

Keywords	car	vehicle	ELV	Truck
disassemb*	w/1	w/1	w/1	w/1
dismantl*	w/1	w/1	w/1	w/1

Fig. 1. Schematic summary of method steps for the literature review (in grey) and the focus group study (in white), including the comparison (lined).

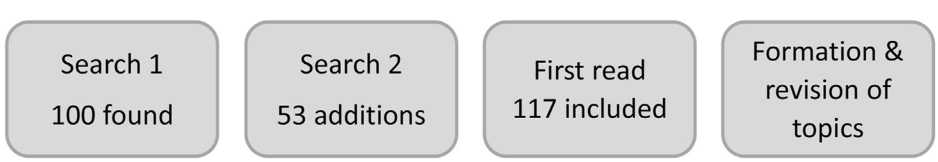

Fig. 2. Literature review process, with identified and included articles.

Table 2
Combination of keywords with the AND operator, used in the first complimentary search.

Keywords	ELV	end of life vehicle
disassemb*	AND	AND
dismantl*	AND	AND

Table 3
Combination of keywords with the w/1 operator, used in the second complimentary search.

Keywords	car	vehicle
recycl*	w/1	w/1

vehicles". The articles were summarized and classified based on the type: literature survey; recycling, production & planning; network design; regulations review, as well as the method(s) used. No literature reviews has been identified which treat the specific role of dismantlers and the dismantling of ELVs, other than in terms of disassemblability by T. F. Go et al. (2011).

This article presents an exploratory review comparing empirical and theoretical findings to evaluate the practical relevance of recent research in the area of ELV dismantling. A literature review focusing on dismantlers and dismantling processes, is combined with results from a focus group study mainly concerning areas of importance for Swedish dismantling industry and end-of-life system.

1.1. Aim and objectives

The aim of this study is to improve ELV management systems from a dismantler perspective by identifying critical factors for efficient dismantling. Accordingly, the objectives are to:

- Identify and categorize the research addressing vehicle dismantling from the last 12 years;
- Identify current and future focus areas for car dismantlers in Sweden;
- Compare the findings from the literature and empirical studies to identify research gaps; and
- Identify areas for future research based on this gap analysis.

The literature analysis focused on vehicles used for the transportation of passengers or goods on roads. Thus, other means of transport are excluded. It also focused on dismantlers, thus resulting in different issues and priorities than from a recycler's perspective. The empirical evidence collected focused on dismantlers operating in Sweden, but also included insights from other Nordic countries and the United Kingdom; however the findings are likely generalizable to other industrialized countries with similar fleet composition, ELV management systems and similar national contexts (especially for countries following the ELV directive).

2. Method

A mixed-method approach similar to a concurrent embedded design was used. The study was mixed in terms of data collection with a structured literature review (theoretical) and a focus group study (empirical), and in terms of analysis with primarily qualitative but also quantitative elements (Creswell and Plano Clark, 2011).

To minimize researchers' bias in the analysis, adaptions of method sequencing were made, see Fig. 1. Data was collected from the focus group and not further analyzed. Thereafter the literature review was undertaken in its entirety by the author. Subsequently the focus group data was analyzed and compared to the literature findings, and thereafter validated in a second focus group.

2.1. Literature review

The literature review aimed to explore current state-of-the-art by analyzing a representative selection of literature following the review process in Fig. 2.

The search was conducted in the scientific database *Scopus* which covers a broad range of sources where End-of-Life topics are published.

Literature search 1: The keywords listed in Table 1 were used to identify research articles on vehicle dismantling and disassembly. These keywords were combined through the proximity operator "w/1", thus allowing phrases as "vehicle dismantling" and "dismantling scrap vehicles". The use of w/1 was adopted after initial searches with the "and" operator, generating over 1100 articles of which many were irrelevant, for example "vehicle" and "dismantle" are used, albeit differently, in the medical field.

The search was limited to articles written in English and published between 2007 and 2019. Further exclusion of articles in the search process was not desired, since literature connected to ELVs are published in a variety of fields and sources. The exact search string used was: TITLE-ABS-KEY ((car W/1 dismantl*) OR (car W/1 disassemb*) OR (vehicl* W/1 dismantl*) OR (vehicl* W/1 disassemb*) OR (elv W/1 dismantl*) OR (elv W/1 disassemb*)(truck W/1 dismantl*) OR (truck W/1 disassemb*)) AND PUBYEAR > 2006 AND LIMIT-TO (LANGUAGE, "English"). This search generated 100 articles.

As a review should contain the most relevant and significant research on the topic (Saunders and Rojon, 2011), two additional searches were conducted to mitigate the risk of missing too many relevant articles. Inclusion was based on a citation count of at least 30, or 10 for articles published between 2015 and 2019.

Literature search 2: To loosen the w/1 restrictions from the first search and include articles not using the abbreviation ELV, the keyword "end of life vehicle" was included (Table 2).

Even if the primary focus of the literature study is the dismantling of vehicles, the use of the word recycling is prominent in literature regarding a vehicle's end of life. Therefore, an addition with "recycl*" was made, see Table 3.

The additional searches generated 68 articles, with 15 duplicates from the first search. Hence, 53 articles were added to the literature review.

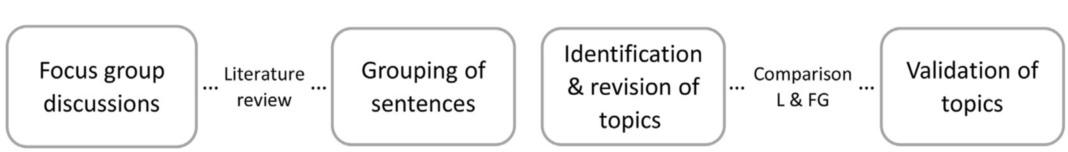

Fig. 3. Focus group method and analysis process.

Table 4
Workshop participants and stakeholders represented (life cycle stage).

Stakeholder	Number of participants
Dismantling	2
Industry associations	1
Recycling (Shredding)	2
Manufacturing	3
Research	6
Total	14

Table 5
The participants present during the validation workshop and the life cycle stage they represent.

Participants	Number
Dismantling	1
Industry associations	2
Recycling (Shredding)	1
Manufacturing	3
Research	3
Total	10

2.1.1. Inclusion of literature

Articles were included after reading the abstract. For transparent inclusion criteria, advised by Vom Brocke et al. (2009), only articles not related to end-of-life treatment of road vehicles were excluded. Articles in which the dismantling is mentioned as merely (1) the material source or (2) an area for further consideration or research, were excluded from the study.

From the total 153 articles, 117 were considered relevant for inclusion in the literature review.

2.1.2. Analysis

This article focuses on the topics covered in the articles, rather than summarizing them, as recommended by Webster and Watson (2002). This enables a comparison of literature and results from the focus groups. To identify the topics, the analysis of the literature review was carried out in stages.

The first part of the analysis used grounded theory in accordance with Wolfswinkel et al. (2013). Grounded theory allowed analytic categories to emerge from the abstracts, letting the data speak through an iterative data addition and analysis process (Charmaz, 2014). Moreover, grounded theory was used to form topics and keywords freely rather than having predetermined alternatives. However, there was a predetermination to connect the articles to different system levels.

Each abstract was read, summarized and preliminary system levels and topics were extracted. System levels refer to the articles' main actor(s) or stakeholder(s). Topics shortly describe the articles' objectives. As further abstracts were studied, the topics were refined. Subsequently the articles were grouped based on system level, and the topics were further iterated. Some iterations on system level of articles were also made. The topics were specified further into subtopics to describe the area in more details. The aim in this phase was to keep an open mind and identify the most important aspects, as recommended by Hart (1998).

2.2. Focus groups

To identify areas important for the ELV industry, a focus group study was used with representatives from industry and research.

Table 6
Sources and corresponding number of published articles.

Source title	Number of articles
Waste Management	12
Journal of Cleaner Production	11
Resources, Conservation & Recycling	10
Procedia CIRP	5
Journal of Material Cycles and Waste Management	4
Advanced Materials Research	3
Environmental Science and Technology	3
Waste Management & Research	3
Other 61 sources	66
Total	117

The first occurrence was held in the spring of 2017 as a part of the research project EXPLORE, "*Exploring the opportunities for advancing vehicle recycling industrialization*"[1] addressing efficient end-of-life treatment of vehicles in Sweden. An overview of the focus group process, data collection, analysis and validation, is shown in Fig. 3.

The workshop had 14 participants, including two from companies dismantling cars and one from the Swedish Car Recyclers Association, which organizes the authorized Swedish dismantlers (Table 4). All participants are experts in areas related to vehicle dismantling, thus bringing in-depth knowledge as well as different perspectives on the treatment of ELVs and surrounding aspects.

2.2.1. Data collection

Participants were asked to discuss questions in groups of four, resembling the mini-group as described by Greenbaum (1998). Several smaller groups are preferred to few larger groups to promote discussions between all participants and deeper reflections (Fern, 1982). Each group had representatives from both industry and research to generate a broad discussion. Two sessions were held, with discussions in small groups, both followed by presentations. Between the sessions participants switched groups. To avoid individuals to dominate the discussion and to allow greater number of ideas (Fern, 1982), the participants were encouraged to reflect on their own for 5–10 min before discussing in groups for approximately 1 h.

The questions used were created by the research consortium of the project to gain insight into the future of ELV treatment. The four questions discussed were (translated from Swedish):

- What type of vehicles will be put on the market in short- (5 year) and long-term (20 year) and how will this affect manufacturers, dismantlers and recyclers to achieve effective material recycling?
- What will the dismantling and recycling business for vehicles be like in short- (5 year) and long-term (20 years), considering the number of companies, cooperation, purchases, sales, number of cars etc.?
- What type of technology and technical aids will be needed for dismantlers and recyclers to achieve more effective and efficient material recycling in the future?
- What will the future workplace for vehicle disassemblers (operators) be like, what competence and information will they need to achieve efficient and effective material recycling?

2.2.2. Analysis

An approach of content analysis and grounded theory was used to generate keywords, similar to section 2.1.2 (Wolfswinkel et al., 2013). Firstly, statements including the same keywords were compiled into new sentences and grouped based on the life cycle actor involved. Thereafter, keyword groups were connected to the

[1] More about the project can be found at(in Swedish) https://closingtheloop.se/aktuella-projekt/explore/.

topics identified in the literature section, thus, enabling a structured comparison. New topics were formed if needed.

2.2.3. Validation of empirical results

As the initial focus group was conducted in spring of 2017, another was organized in the end of 2019 to ensure industrial relevance of the topics identified (validation phase). This second focus group included ten participants, of which five participated in the first round (Table 5). One of the participants was from the Swedish Association for Motor Retail Trades and Repairs and one from the Swedish Car Recyclers Association, which organizes the authorized dismantlers in Sweden.

The topics created were presented together with the areas considered as the most important in the first round. The participants discussed the relevance of the topics and whether the same ones were most prominent.

3. Results

This section presents the identified literature. Followed by results from both the literature review and the focus groups connected to the system levels and topics identified.

3.1. Literature review

A total of 69 sources were identified for the 117 articles included in the literature review (Table 6). Three sources stand out with roughly 30% of the articles published in either “Waste Management”, “Journal of Cleaner Production” or “Resources, Conservation & Recycling”.

Five system levels (actors) were identified: designer; manufacturer; dismantler; recycler/shredder; and the end-of-life (EOL) system. The EOL system encompasses the other four actors as well as other relevant stakeholders, such as regulators and countries. To avoid unnecessarily complex categorizations, the EOL system level was used for articles taking a holistic perspective, covering at least two actors. The distribution of published studies per year and per system level varied (Fig. 4). Roughly 50% of the articles included were published between 2013 and 2016. As expected, most publications connected to the EOL system and dismantler levels with 45 and 46 articles respectively.

3.2. Topics and subtopics identified

The topics derived from the literature review and analysis of the focus group discussions are presented based on the actors involved in a vehicle’s end-of-life stages (system levels). The results are arranged from wider to more hands-on topics. For each specific topic there is, when applicable, both a short description based on the connected literature as well as a summary of the focus group results. When no relating results were identified, the cell is blank.

The designer and manufacturer system levels connect to their role in the end of a vehicle’s lifecycle. The EOL system level takes a holistic perspective, connecting to multiple actors or all system levels (for further details see paragraph 3.1). The topics for the EOL systems level are presented starting with those relating to facilitators such as regulations and ending with selection of which actors or rather processes, such as dismantling or shredding, to use in the EOL system. The dismantler system level includes both strategic decisions and operational considerations. The shredder and recycler system level concerns both management and hands on methods. For the results, see Table 7, where all articles and the focus group results treating the specific sub-topics are presented with some details.

3.3. Synthesis of academic results

The literature provides a variety of perspectives, even within topics. To identify the areas well covered in current research, the quantity of articles connected to each topic was considered. Six topics had ten or more references each, whereof all the topics at the EOL system level. This was expected considering the breadth of this system level and thus the volume of literature associate with it. The dismantler level was similarly well covered with the same number of articles; again an expected result given the focus on this study. Though, it generated more detailed topics as well as a wider spread in research, compared to the EOL system level. The research topics best covered in this literature review were (ten or more articles):

- Design for EOL (designer level);
- Facilitators (EOL system level);
- Design and optimization (EOL system level);
- System performance (EOL system level);
- Process strategy and selection (EOL system level); and

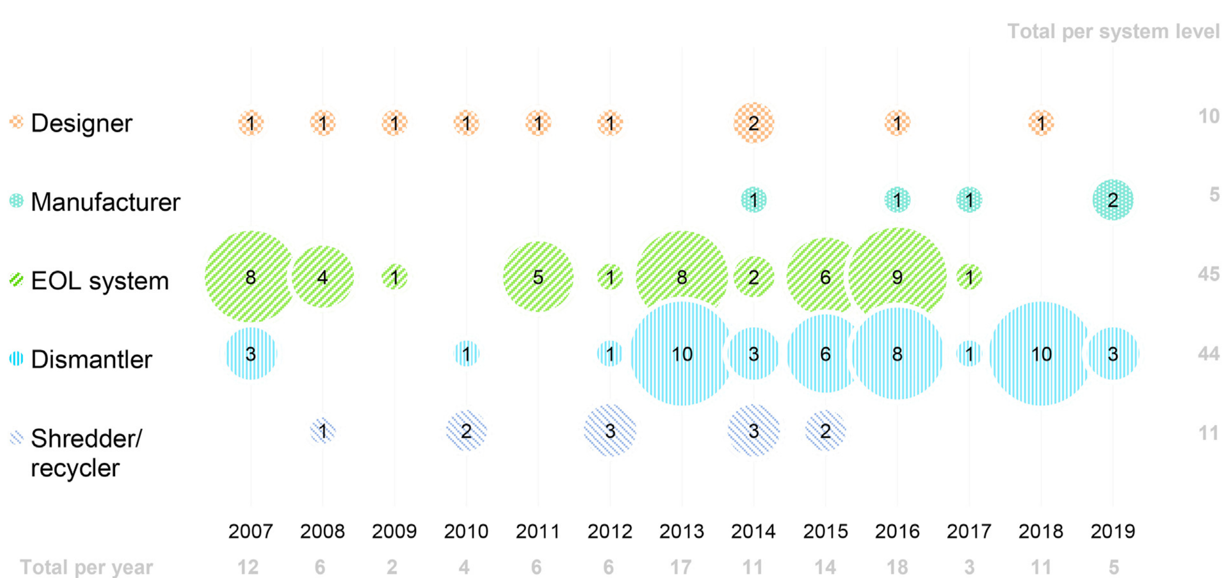

Fig. 4. Distribution of publications per year for each system level (life cycle actor).

- Site pollution and contamination (dismantler level)

Within the dismantler system level three topics apart from the one above stands out:

- Process selection
- Plant design
- Battery recycling

Fig. 5 shows the distribution of articles reviewed across the system levels and topics identified.

3.4. Synthesis and validation of empirical results

The most detailed and prominent findings from the focus group were concentrated at the dismantler level. In which, management topics, such as business incentives and structures, were discussed alongside technical topics, such as copper recycling and difficulties in recycling composites. The subtopics considered as the most essential in the focus group were identified based on the amount of discussion and engagement compared to other topics and the expressed urgency and attention needed in the future by the participants themselves. The topics are (all at dismantler level):

- Plastics recycling – Economic and environmental evaluation;
- Battery recycling – Processing management and development;
- Workforce – competence and cognitive support; and
- Choosing large investments and ownership structures(present in the topics below);
  - Process selection – Strategic considerations;
  - Physical automation – Operator support and production improvement;
  - Business incentives - Economic sustainability and profit.

The participants in the second focus group expected the topics to be outdated. However, when displayed, they completely agreed on the selection of the most crucial topics. Thus, despite ongoing research and improvement work in the industry, many issues have yet to be resolved.

4. Discussion

This section discusses the theoretical and empirical findings from this exploratory study. Other important aspects for ELV management, such as functional recycling, were not addressed in this study but are highlighted in the conclusion as proposed further work.

4.1. Comparison of literature and empirical results

While contrasting the theoretical and empirical results, both similarities and differences are noted. Several of the subtopics are either not researched or discussed in the focus group, see blanks in Table 7. Part of this caused by the research design, with the first focus group being held before conducting the literature review. Thus, the topics had not emerged, see paragraph 4.3.3 for details. However, there is also a difference in focus with researchers being able to study the ideal state, whereas, the discussions in the focus group was focusing on issues closer to the business. This is especially notable at the *EOL system level* were several strategic matters are researched, e.g. dismantler site location and measurement principles of environmental impact.

A majority of the articles in this study focus on light vehicles (cars and commercial-light vehicles) whereas the articles, which explicitly include heavy-duty vehicles (here limited to trucks) are few. In the focus group the majority of the focus was on the light side, however, the heavy side was considered. The sup topic results at *manufacturer* and *recycler level* apply to both light and heavy vehicles as do several of the topics on *dismantler level* and some for the *EOL system level*. The literature on heavy-duty ELVs is limited, as is the sample in this article. However, there are studies of improving dismantling and designing the facility e.g. by Saidani et al. (2020), Almusallam et al. (2013) and Y. K. Hao and Hasan (2016).

Overall, despite the strong focus on dismantling, it is clear that several of the issues are cross-cutting numerous research areas and involves many stakeholders, as evidenced by the volume of literature found at different system levels and especially at *EOL system level*. For example, *process strategy and selection* (EOL system level) is strongly linked to dismantling as most of the articles treat decisions on level of disassembly versus shredding.

Below results concern the areas judged as extra prominent and urgent to handle by the participants in the focus group. Therefore, several important matters as metals were not deemed as part of the major topics, although, e.g. functional recycling is too low for scarce metals(Andersson et al., 2017b). To elaborate; the Swedish vehicle recycling was initiated around and motivated by recycling metals a century ago, thus, it is a well known area of importance(Andersson et al., 2017a). Despite this, improvements are investigated and needed (Andersson et al., 2017a), incentive systems and information from manufacturers were considered key enablers in the focus group to improved functional recycling.

4.2. Critical focus group topics and related in-depth research

This section elaborates the discussions from the focus groups on the most critical topics and the corresponding research, to end each topic with possible research opportunities.

Battery recycling. The increase in electrified vehicles and how they should be treated to avoid accidents in the dismantling facility is highly important for practitioners. Risks are present in all sorts of handling of electric vehicles and hybrid electric vehicles, high voltage systems and batteries. There are major concerns regarding identification and handling of batteries before, during and after dismantling, e.g. lifting vehicles with forklifts which requires accurate identification of electric vehicles, and proper storing of dismantled batteries. The research articles included in this study cover some of those areas, though mostly in stages after dismantling ELVs, such as aspects of storing shredded batteries (Grützke et al., 2015) and practices of dismantling the battery itself (Buzatu and Ghica, 2013; Cerdas et al., 2018). There are also many articles regarding alternative waste management solutions for batteries which are not captured in this literature review, such as those by Hobbs et al. (2017); Maharshi and Reddy K (2019); Natkunaraiah and Scharf (2015). Despite the research interest, the attention to vehicle dismantlers is low. Further research is needed (1) to understand how much and what steps to undertake at vehicle dismantling sites, and (2) to create efficient recycling chains for batteries including the vehicle dismantler as a key enabler.

Plastic recycling. Concerns about handling increasing amount of plastics in the vehicles were highlighted by the dismantling representatives and discussed in the focus group. More efficient and profitable plastic handling is needed, compared to the current practice of shredding most of it with the vehicle hulk. This was recognized, in the focus group, as critical to maintain and increase the recycling rate of vehicles. This issue was researched already in the 90s (Bellmann and Khare, 1999; Hock and Maten, 1993) and it has yet to be resolved. For example Miller et al. (2014) identified cost efficient recovery infrastructures as one of the issues, also voiced in the focus group. In this review, several authors addressed

Table 7
Topics (bold) and subtopics (italics) identified from literature and the focus group with corresponding decription of the results.

Literature	Focus group
Designer level **Design for EOL -** *Methods for measuring disassemblability*	
Presentation of existing and evaluation of new methods (Afrinaldi et al., 2009; Berzi et al., 2016; T. F. Go et al., 2011)	–
Design for EOL - *Requirements, guidelines and trends in these*	
Both holistic and specific examples of design requirements from EOL perspective e.g. joining and disbonding (Bennett, 2012; Froelich et al., 2007; Gagunov et al., 2018; Lu et al., 2014; A. Santini et al., 2010; Sopher, 2008; J. Tian and Chen, 2014)	Specific examples of difficulties with operations such as draining fuel tanks, and material recognition were given. Physical design changes to enhance disassemblability was not anticipated.
Manufacturer level **Vehicle characteristics** - *Material composition*	
Determination of current contents on holistic scale and amounts of specific materials in vehicles (Restrepo et al., 2017, 2019; Xu et al., 2016; Yano et al., 2019)	Changes in material composition with further inclusion of lightweight materials, plastics and composites were expected.
Information sharing - *Dismantling instructions for vehicle models*	
Exemplifies creation and usage of information and instructions to support operators, to ultimately increase the recycling rate (Kryaskov & Gagunov, 2014)	Improved information is needed on; how to best dismantle difficult components; for identification of materials in (hidden) vehicle components; and for recognition of vehicles with larger batteries.
EOL System level **Facilitators -** *Regulations effects on the system*	
Effects of regulations on performance of actors and EOL system, design and environmental performance were evaluated (Gerrard and Kandlikar, 2007; Ignatenko et al., 2007; Miemczyk and Graves, 2007; Smink, 2007; Smith and Crotty, 2008)	Further legal requirements and stimulating measures were discussed as means to increase efficiency of (functional) material recycling for both light and heavy vehicles.
Facilitators - *Comparison of regulations between countries*	
The comparisons were aimed at facilitating implementation of efficient policies (Che et al., 2011; Chen et al., 2015; Sakai et al., 2007; Sakai et al., 2014; L. Wang and Chen, 2013b; Zhao and Chen, 2011)	–
Facilitators - *General facilitators*	
–	Increases in service economy and new ownership forms together with arrival of autonomous vehicles will change the conditions for the End-of-life business and all actors.
Design and optimization - *The network its actors and interactions*	
Optimization of the amount of actors, their location and interaction between each other were treated through different models (Demirel et al., 2016; Ene and Öztürk, 2015; Hendrickson et al., 2015; Krikke et al., 2008; Mansour and Zarei, 2008; F. Zhou et al., 2016a)	Amounts of dismantling facilities will decrease, more specialists on treating specific components will appear. To increase reuse and recycling cooperation between different actors is necessary. Logistics to and from sites needs improvement, no use of advanced methods.
Design and optimization - *Dismantling site location*	
Decision support for managers of the system was developed for location decisions in regions and countries (Gołę;biewski et al., 2013; Pavlovic et al., 2011)	–
Design and optimization - *Allocation of ELVs and materials*	
Modelling as decision support for managers allocating ELVs and materials among actors in the EOL system (Simic, 2015b, 2016a, 2016b, 2016c; Simic and Dimitrijevic, 2015)	–
System performance - *Environmental impact*	
Performance and improvements studied through LCA on the EOL system or off a vehicle (Erses Yay and Yay, 2013; H. Hao et al., 2017; Jeong et al., 2007; W. Li et al., 2016b; S. Sawyer-Beaulieu and Tam, 2015)	–
System performance - *Recycling rate improvements*	
Are identified for either countries or specific materials (Cucchiella et al., 2016; Løvik et al., 2014; Muñoz et al., 2009; A. Santini et al., 2011; L. Wang and Chen, 2013a; Z. Q. Zhou et al., 2012)	Functional recycling of, especially scarce, materials have to increase to avoid depletion.
Process strategy and selection - *Environmental impact*	
Determination of suitable mix of dismantling and shredding levels based on the impact (Belboom et al., 2016; Fonseca et al., 2013; S. S. Sawyer-Beaulieu and Tam, 2008; Schmid et al., 2016; Tasala Gradin et al., 2013)	Dismantling levels versus shredding was mentioned but not discussed at length, because of economic considerations.
Process strategy and selection - *Economic evaluation*	
Determination of suitable mix of dismantling and shredding levels based on the impact (Barakat and Urbanic, 2011; Coates and Rahimifard, 2007; Dalmijn and De Jong, 2007; Farel et al., 2013; Kovács, 2013)	–

(continued on next page)

Table 7 (*continued*)

Literature	Focus group
Dismantler level	
Business incentives - *Economic sustainability and profit*	
Considered situations are: starting a new dismantling facility, the unregulated market, and modelling of uncertainty (Keivanpour et al., 2013; Mohan and Amit, 2018; Xia et al., 2016)	In the coming years the dismantling industry in Sweden will change into fewer but bigger dismantlers and corporate groups. The standard of good dismantlers will be elevated but not all companies will be profitable. Economic incentives might be needed for pure ELVs.
Plant design - *Facility and workstation layout*	
Evaluation of layout options, also considering aspects of ergonomics and placement of equipment (Acaccia et al., 2007; Almusallam et al., 2013; Berzi et al., 2013; Kazmierczak et al., 2007; Neumann et al., 2018; Sohn and Park, 2014; Zhang and Chen, 2018; Z. Zhou et al., 2016b)	Discussion of options to increase performance, such as separated flows for different drivelines, possibly arrange based on line layout.
Process selection - *Strategic consideration*	
Degree of manual work versus mechanization of processes considering waste and environmental impact and IoT adoption at dismantling sites (M. Badida et al., 2018; Miroslav Badida et al., 2017; El Halabi et al., 2015; Peng et al., 2014; Jin Tian and Chen, 2016; Yi and Park, 2015)	Increased mechanization needed for specific parts as cables to improve economy and material recycling. The decision of when to invest in new or improved processes is important.
Battery recycling - *Processing management and development*	
How to disassemble batteries and treat dismantled parts and the regulations applicable were studied (Buzatu and Ghica, 2013; Elwert et al., 2018; Grützke et al., 2015; Träger et al., 2015)	There is uncertainty about how to treat the batteries and electrical system safely and efficient. Information regarding battery type and placement in the vehicle was desired for (hybrid) electric vehicles. There are worries regarding increased electrification and its effects on work environment, sound routines should be established.
Battery recycling - *Automation of disassembly*	
Automation trials and design, also deducing potential benefits(Cerdas et al., 2018; Sonoc et al., 2015; Wegener et al., 2015)	–
Plastics recycling - *Economic and environmental evaluation*	
Treated through: a business case, and effects of increased recycling of plastics (Duval and Maclean, 2007; Zhao et al., 2012)	Currently not entirely economically beneficial but needed for a good recycling and the environment. Transports needs to be cost effective, likely enabled trough size reduction.
Physical automation - *Operator support and production improvement*	
Fixtures, dismantling tools and exoskeletons supporting operators were considered (Bei et al., 2018; Constantinescu et al., 2016; Szotkowski and Mrkvica, 2018)	More automated and advanced tools will be available and used in the future. The right ones needs to be selected.
Process selection - *Operative decision and support*	
Decision on process steps and parts to dismantle for each specific vehicle considering economic and environmental effects (Clappier et al., 2014; Nowakowski, 2013)	Support considering multiple aspects in decisions of which components and spare parts to disassemble would be beneficial.
Process performance and improvements - *Assessment and management*	
Considered in general, as well as through Lean adoption, line balancing and emergy as a sustainability measure (Y. K. Hao and Hasan, 2016; Islam et al., 2018; Pan and Li, 2016; Zuo et al., 2013)	Processes will be made more effective through general fine tuning. Increased automation and equipment for electric vehicles could also be used.
Workforce - *Competence and cognitive support*	
–	Mechanically skilled workers are needed. They should also handle digital support tools and more automatic and advanced equipment as well as electrical systems. However, it is hard to attract competent workers. More and good digital support to workers is both anticipated and desired in the future.
Site pollution and contamination - *Occurrence, health risk and work environment*	
Studied pollutants in soil, air and car seats as well as the connected health and work environmental risks (Anh et al., 2019; Gou et al., 2016; Khaled et al., 2018; Man et al., 2013a; Man et al., 2013b; Man et al., 2010; Nyholm et al., 2013; Y. Wang et al., 2018; Wu et al., 2013)	–
Site pollution and contamination - *Methods for prevention*	
Removal of leaked vehicle fluids and wastewater treatment to mitigate contamination (Ghimpusan et al., 2016; Ubowska and Olawa, 2019)	–
Recycler level	
Recycling management - *Production management and overview of development*	
ASR management overview, as well as decision support for production planning and supply (Cossu and Lai, 2015; Simic, 2015a; Simic and Dimitrijevic, 2012)	Recycling companies' structure and large size are anticipated to remain in the future.
ASR - *Material characterization*	
Development of characterization techniques, and effects on ASR from further dismantling (Fiore et al., 2012; Serranti and Bonifazi, 2010)	Technical improvements in automated characterization are needed.
ASR treatment - *Methods for recovery of materials and energy*	

Table 7 (*continued*)

Literature	Focus group
To create value from ASR several treatment methods were developed and evaluated(Lopes et al., 2008; Ni and Chen, 2014; Ohno et al., 2014; Alessandro Santini et al., 2012; Tai and He, 2014; Vigano et al., 2010)	New and improved separation techniques needs to be used.

plastic, such as examples for design of vehicles (Froelich et al., 2007; J. Tian and Chen, 2014), and in process selection (M. Badida et al., 2018; Belboom et al., 2016; Tasala Gradin et al., 2013) as well as in dismantling (Zhao et al., 2012) and ASR treatment (Ni and Chen, 2014; Alessandro Santini et al., 2012). Further, Duval and Maclean (2007) studied a plastics recycling network for a large dismantler and concluded that it would be environmentally but not financially beneficial to participate. Although plastics recycling is a well-researched area, it was not a strong topic in the literature sample reviewed, likely as it is not always connected to dismantling activities and not specific for ELVs. Despite previous research and recent technological progress, effective and economically viable recycling chains for automotive plastics are not in place in several countries, as of end-2019. Thus, further work is needed to identify more sustainable recycling chains. This motivated the research efforts to create business opportunities and an effective plastics recycling chain for ELVs in the Explore project, mentioned earlier (Fängström and Yari, 2017).

Workforce. From the results, it was concluded that the role of operators in the dismantling industry has not been researched as extensively as other topics. When workers are considered, the focus has mainly been on physical factors, such as physical support or ergonomics. Regarding cognitive support, Kryaskov and Gagunov (2014) created a catalogue with graphical material on how to dismantle light vehicles with the aim to increase recyclability. Lie et al. (2018) also proposed a knowledge sharing system in remanufacturing, which instructs the operators in each step of the process. These issues are given much attention within manufacturing, partly due to factors as standardization, complexity in production, industry 4.0 and information needed to handle changing work tasks, e.g. Gorecky et al. (2014); D. Li et al. (2016a); Parmentier et al. (2019); Tarrar et al. (2020). Dismantlers anticipate the operators and their skills to be highly important, and further, addressed the issues of recruiting competent staff as well as information requirements for the workers. The need for instructions or similar material aiding operators in identifying and dismantling

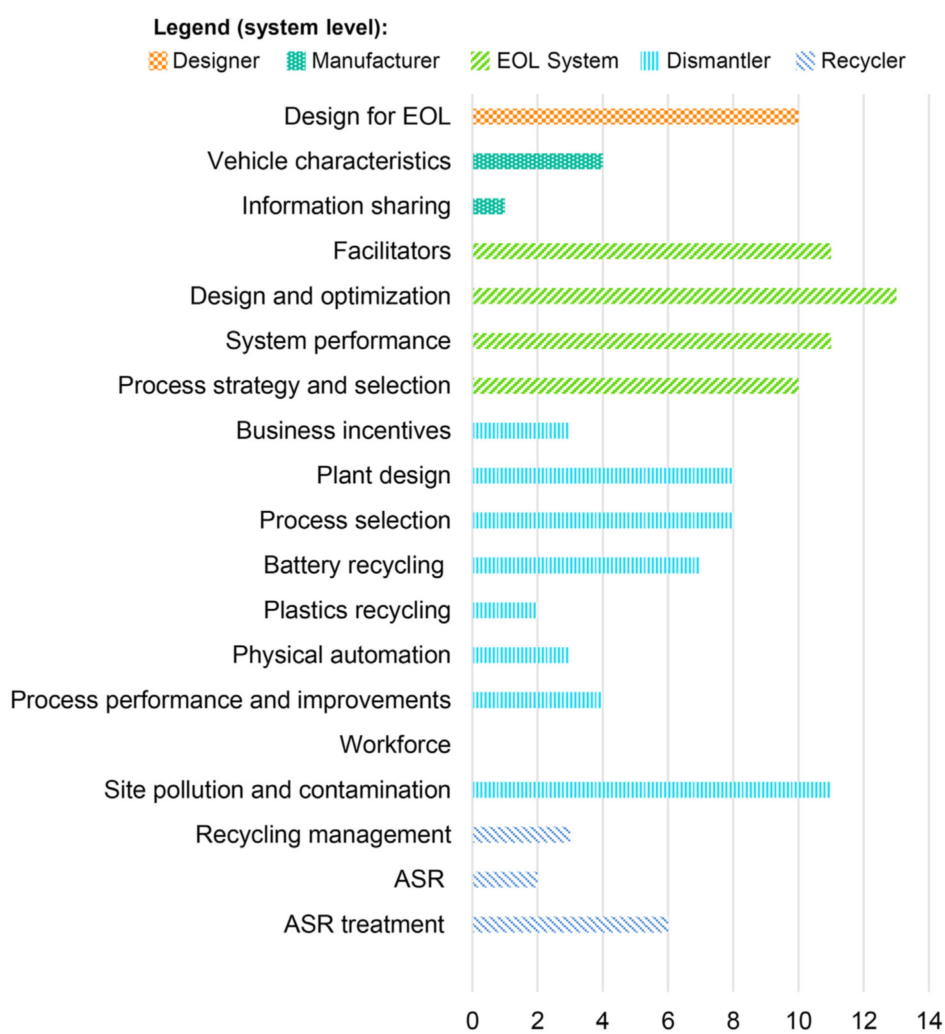

Fig. 5. Topics identified and distribution of articles included in the literature review.

components was addressed in all focus groups and in meetings with dismantlers. Thus, cognitive support for operators is critical for industry, but has not been much researched for end-of-life actors like dismantlers. This area is also relevant for the manufacturers as it presents an immediate solution to increase recyclability without physically changing products, as suggested by Kryaskov and Gagunov (2014). Addressing the unique needs and challenges of cognitive aspects is particularly relevant for actors with little own control of the products, such as the dismantlers. This research topic would give a new perspective to the body of research surrounding the EOL system and its actors as well as in the area of cognitive support and operator assistance.

Investments and ownership structure. Industry anticipates larger changes in ownership structures of dismantlers (corporate chains), new market for autonomous cars, as well as longer life cycles of vehicles through product life extension and services such as leasing, then captured in the literature. This is in line with efforts such as by T. Go et al. (2015) who reviewed, defined and stressed the importance of multiple generation life cycles to enable increased product sustainability. New service-based business models, such as leasing and car-sharing, as well as a circular economy strategies for product life extension result in multiple life cycles and new vehicle ownership structures. This may ultimately result in fewer cars in circulation and thus fewer vehicles to handle in the EOL chain in the long-term. However, the number of ELVs is still increasing in many countries and will continue to do so in the short-to medium-term. Possible research topics are: (1) how to (re) design the EOL system to be efficient, generate profit and the lowest environmental impact; and (2) how to promote cooperation between actors across all stages of the product life cycle, possibly making use of industry 4.0 technologies and big data analytics. Although reducing number of vehicles is not in focus yet, several researchers are considering future scenarios in designing and optimizing the EOL system. See topics on *Design and optimization* of the EOL system, e.g. Demirel et al. (2016); Mansour and Zarei (2008); Simic (2016c).

There is a low number of case studies at dismantler sites, especially regarding process improvements. Which is even more evident for heavy-duty vehicles (Saidani et al., 2020). Karagoz et al. (2019) reached the same conclusion at a general EOL systems level. They also concluded that most researchers focus on the managerial perspective. This review bears resemblance with the review by Karagoz et al. (2019) as articles from the entire EOL system were considered in both articles, which few other reviews do. However, there are important differences in the results as they used fixed categories whereas this review freely explored qualitative aspects. Furthermore, the novelty of this review is the inclusion of the focus group study to compare literature findings and empirical findings directly from industry, and the focus on the dismantlers and their role in the ELV processing chain.

4.3. Validity

Validity and rigor of the study are discussed based on methodological considerations regarding the sample and the participants, as well as questions used in the focus groups.

4.3.1. Literature sample relevance

The aim of the study was exploratory. The literature review included 117 articles aiming to cover a representative sample of research articles. It is hard to estimate how representative this review is and how exhaustive it covers the total body of literature surrounding dismantlers and dismantling, since the area is multidisciplinary. The three searches conducted generated 421 documents in total, as of November 2019, thus, 36% of the articles were considered; however, there are likely publications not captured in those searches.

The additional searches were conducted to elevate the representativeness of articles included. Strong contributions were merely gained in the plastics and battery topics at the dismantler system level, and at the other system levels. Thus, much research treating the dismantlers was captured through the first search. Despite this the extension generated both depth and width to the review and was considered relevant. Particularly as there are strong connections between the dismantlers and other actors in the ELV system (the essence of the EOL system level) especially on a strategic level, consider issues such as dismantling level versus shredding (see topics “Process selection and strategy” and “Design and optimization” (EOL system level)).

The articles included in the study came from a wide range of sources, which confirms that articles dealing with ELVs are connected to different research fields such as ergonomics, management and environmental science. Therefore, articles are likely missing in this review due to different terminologies and keywords used in some fields. However, the main area of interest, namely dismantling and disassembly of vehicles is more comprehensively covered by the keywords.

4.3.2. Focus group participants

The sample of car dismantlers participating in the workshops is not representative of the entire Swedish, let alone the worlds, vehicle-dismantling industry. They represent relatively large companies that continuously develop their processes. They have also participated in several research projects, indicating proactivity in their management. Nonetheless, areas critical for these dismantlers are very likely important for other dismantlers as well, but possibly in the future depending on present development and operations. Further supported by the trend with larger dismantlers.

Concerns of other dismantlers are to some extent included through the participant representing the organization of authorized Swedish dismantlers, and through those researchers who had visited several other dismantlers before the focus group study. The dismantlers, the aforementioned participant of authorized Swedish dismantlers and two of the researchers has previously visited dismantling sites in other countries (the Nordic countries and United Kingdom) to get inspiration and identify improvement possibilities. Thus, influences on practices has been attained from other countries. However, the focus of the participants was on the current operations in Sweden, thus, importance of workforce is not possible to generalize without considering specific conditions. The wages in Sweden are rather high and there is competition for skilled mechanics between dismantlers and repair workshops, which cannot be assumed in many countries.

The issues of vehicle batteries and plastics are deemed interesting with strong support through the amount of research and the topics, thus, should be possible to generalize. Regarding ownership structures, similarities could be anticipated in richer countries as vehicle ownership is common and there is an increased interest in mobility services, circular economy and T. Go et al. (2015) stresses importance of further life cycles. Whereas vehicle ownership in many developing countries could be expected to increase due to economic growth, causing issues of building the EOL system rather than adapting it to lower volumes (see topics of Design and optimization — EOL system level).

To summarize the empirical evidence collected focused on dismantlers operating in Sweden, but also included insights from other countries; however the findings are likely generalizable to other industrialized countries with similar fleet composition, ELV management systems, national contexts (especially for countries following the ELV directive) and workforce situation.

4.3.3. Focus group questions

Part of the differences between literature and empirical results are caused by the questions discussed during the focus group. The questions were created before the literature review was conducted and designed to enable free discussions. This design was selected in an attempt to explore the topics with as little bias as possible, and be open to unexplored ideas, which may have not emerged if the questions were formulated based on findings from the literature review.

5. Conclusion

This article confirms that management of ELVs is highly multidisciplinary. Research work has been published in a number of sources, of which three stands out—namely "Waste Management", "Journal of Cleaner Production" and "Resources, Conservation & Recycling"—with different perspectives but a common vision of decreasing the negative impact from a vehicle's end of life. The dismantler and their processes are the main focus in this article and factors of importance for efficient dismantling were identified. There are similarities in topics addressed in the published literature and from empirical data collected in the focus group. However, there are differences in the topics considered as critical for vehicle dismantling in Sweden and those being researched. The most prominent research topics from the literature review were:

- Design for End-of-Life (designer level);
- Facilitators (EOL system level);
- Design and optimization (EOL system level);
- System performance (EOL system level);
- Process strategy and selection (EOL system level); and
- Site pollution and contamination (dismantler level)

The most prominent topics from the focus groups are listed below. These are commented with areas to consider for practitioners and researchers, as the differences identified indicates potential gaps in knowledge and practice (see 4.1 and 4.2).

1) Plastics recycling – Economic and environmental evaluation;
2) Battery recycling – Processing management and development;

Efficient handling and what steps to undertake at vehicle dismantling sites for batteries from electrified vehicles, needs attention. Further, to create efficient recycling chains for plastics as well as batteries, where the vehicle dismantler is a key enabler.

3) Workforce – competence and cognitive support;

Research on how and which cognitive support and information to give operators would advance literature on both EOL of products as well as cognitive support.

4) Investments and vehicle ownership structure;
   a) Process selection – Strategic considerations;
   b) Physical automation – Operator support and production improvement; and
   c) Facilitators - General facilitators (EOL system level).

The effects on and new management of the end-of-life chain required by alterations in vehicle ownership structures, autonomous vehicles, and multiple life cycles.

Furthermore, literature is limited on (1) End-of-life management of heavy-duty vehicles, both as case and theoretical studies and (2) case studies at dismantling sites in general and process improvements in particular.

Additionally, there are areas not covered in this paper, which are of high importance to advance ELV management towards circular economy. Some of these aspects, which are subject to upcoming research and contemplation of practitioners, are:

- Functional recycling of metals;
- Strengthened policies and legislations;
- Illegal export of ELVs; and
- Diverging interests of actors in the EOL system.

CRediT authorship contribution statement

Malin Tarrar: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Mélanie Despeisse:** Writing – original draft, Writing – review & editing, Visualization. **Björn Johansson:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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